TENSILE BEHAVIOUR OF RC MEMBER SUBJECTED TO AAR

Ryosuke Takahashi[1,*], Yasuhiko Sato[2], Toru Yamaji[3]

[1]University of Yamanashi, Dept. of Civil and Environmental Engineering,
4-3-11 Takeda KOFU, Japan

[2]Hokkaido University, Division of Built Environment,
N13-W8 SAPPORO, Japan

[3]Port and Airport Research Institute, Materials Division,
3-1-1 Nagase YOKOSUKA, Japan

Abstract

Prism RC test specimens are made with reactive coarse aggregate. Reinforcement ratio and diameter of reinforcing bar are factors. They are submerged in hot sea water is conducted to accelerate AAR. Tensile load is applied to them through reinforcing bar after the procedure.

In the observation of average concrete stress - strain relationship obtained from the test results, it is clarified that the relationship is different from undamaged concrete and divided into 4 regions expressed by 8 factors. Some of these factors are formularized with a coefficient relating to crack opening caused by AAR expansion. Tensile behaviour is related to damage of AAR expansion in this study.

Keywords: AAR, tensile behaviour, average concrete stress, confinement effect, bond

1 INTRODUCTION

Appropriate management of the concrete structure requires an accurate evaluation of deteriorated structural performance. Though many early researches on Alkali Aggregate Reaction (AAR) clarified its mechanism gradually and these outcomes are useful for prevention and countermeasure against AAR, there are still unclear points on how much AAR degrades a structural performance.

The accurate evaluation of structural performance requires quantified effect of AAR damage to the performance. Though there are early studies about the effect of AAR to the structural performance in a macroscopic view such as decrease of the flexural strength, there are few ones connecting changes of the performance and AAR damage quantitatively. It is difficult to connect the performance and the damage directly, because the damage affects some kinds of fracture mechanics of materials in a member and behaviour of the member is consisted with behaviours of these deteriorated materials.

This study investigates a tensile behaviour of RC member subjected to AAR. Cracks generated by AAR are thought to decrease a confinement effect of concrete around a reinforcing bar and the decrease affects the bond mechanism. This study clarifies the tensile behaviour by one directional tensile test of RC member subjected to AAR and tries to connect the behaviour and the AAR damage such as cracks quantitatively.

2 MATERIALS AND METHODS

2.1 General

Test specimens were submerged into a sea water to accelerate AAR before loading. In this section, outline of the test specimen, the accelerating and the loading procedure is explained.

2.2 Test specimen

Figure 1 illustrates one of prism specimens prepared. A deformed reinforcing bar was set at the centre of the section with an enough bond length to investigate the average behaviour.

Strain on a reinforcing bar and concrete surface were measured during accelerated development of AAR and the loading procedure with strain gauges and a contact gauge measure.

* Correspondence to: rtakahashi@yamanashi.ac.jp

Locations where the gauges and stainless tips of contact gauge measurement are also displayed in Figure 1. The gauges were put on two longitudinal ribs of the reinforcing bar at 5*D* intervals. Two gauges were put on opposite faces at the location to neglect a flexural strain. Tips used for the measurement of concrete surface strain were put on concrete surface at 100 mm intervals with achieve. Because the specimen was submerged in hot sea water to accelerate AAR, stainless tips were used to prevent from corrosion and a boundary between concrete and tip were covered with epoxy plastic to prevent from deterioration of the adhesive.

A certain length from both ends of a reinforcing bar in a specimen is not covered with concrete because a loading machine grabs them to apply tensile load. A couple of strain gauges were additionally put on a bare part of the bar after the acceleration procedure to measure the load applied.

Specification of specimens and properties of reinforcing bars are displayed in Table 1 and Table 2. Main factors considered in this test series are a diameter of the reinforcing bar, *D* and the reinforcement ratio, *p*.

Table 3 and Table 4 show material properties and mixture proportions used for concrete of test specimens. The course aggregate used here is an alkali reactive crushed stone produced in Japan. A type of the rock was not investigated. Moreover, NaOH was added to accelerate the reaction at the mixture. The determinant of NaOH amount was depended on the early study [1] and a workability of fresh concrete.

2.3 AAR acceleration procedure

In order to accelerate AAR, all specimens were submerged into 60 °C natural sea water.
Specimens had finished 7 days moist and 21 days natural curing at the start of the submergence. Concrete cylinder specimens prepared for compressive test were also submerged with RC prism specimens. Steel strain and concrete surface expansion were measured during the submergence. The submergence was continued till steel strain caused by AAR expansion reached 3000 μ (exceeding 2200 μ yield strain for steel) in at least one location.

The bare parts of reinforcing bars were wrapped with an anticorrosion tape made from zinc and covered with a plastic bag to prevent the reinforcing bar from corrosion. Moreover a boundary between the bare part of the bar and the RC part was sealed with silicon to keep chloride away from direct penetrating. No rust was observed from members after this acceleration procedure.

2.4 Tensile loading test

After the AAR acceleration procedure, tensile loading test was conducted. The test setup is shown in Figure 2. Both ends of a reinforcing bar were threaded and connected to high strength steel bars with couplers. One end of connected bar was fixed to a steel frame with an anchor plate and the load was applied to the RC specimen through the other end of the bar by using a centre hole-jack. Loading was terminated before yielding of the bar because there was a possibility that the smaller cross-sectional area of the screw part causing a preceding failure.

3 AAR EXPANSIONS

3.1 Characteristics of AAR deterioration

Concrete properties were investigated with a cylinder-compression test during the AAR acceleration procedure. The test results are displayed in Table 5. Compressive strength in the middle of the procedure shows 1.3 times as high strength as undamaged concrete. This phenomenon is thought to be caused by the incomplete curing. The sea water accelerated curing again because natural curing conducted prior to the submergence was not enough. At the end of the procedure, the strength decreases from that of the middle of the procedure. However, no significant damage is observed on compressive strength because the quantity of decrease is a little. On the other hand, Young's modulus shows great decrease. The modulus at the end of the procedure reached only 63 % of that of undamaged concrete.

In the procedure, expansion, random cracks on concrete cylinders and white solid appearing from them were observed. The details about expansion will be described later. We confirm the occurrence of AAR based on the use of reactive aggregate, the great decrease of Young's modulus and the observation of random cracks, white solid and expansions.

Cracks were also observed on RC specimens. Figure 3 illustrates their patterns on each specimen. The directional cracks along the reinforcing bar shows a confinement effect of the bar on the expansion.

3.2 Characteristics of AAR deterioration

AAR expansive average strain on concrete surface of RC specimens is displayed in Table 6. The confinement effect of the reinforcing bar is also shown in this table. Longitudinal strain is much smaller than crosswise strain among all specimens.

Distributions of longitudinal strain on concrete surface and reinforcing bar after the acceleration procedure are displayed in Figure 4. Strain on the bar shows greater value than 1000 μ on many locations and some of them exceed a yield strain (2200 μ). However, the distribution of T16-014, whose strain reaches yield strain in many locations, shows that the concrete strain is too small to cause the yield of reinforcing bar. Base length of reinforcing bar used in a strain measurement is 5 mm and that of concrete is 100 mm. This great difference is considered as one of reasons of this phenomenon because AAR expansion shows high variability.

4 TENSILE TEST RESULTS

4.1 Strain distribution on reinforcing bar

Figure 5 shows steel strain distribution along a reinforcing bar for every 100 μ average strain under loading test. Strain displayed here doesn't contain strain caused by AAR expansion. In this study, an average strain of a member is defined as an average strain of the reinforcing bar embedded in the member. Black plots in the figure indicate the distribution before theoretical concrete cracking calculated with an experimental formula of undamaged concrete and compressive strength [2]. Although steel strain by AAR expansion reaches yield range in some locations, the shape of the distribution and the intension of the strain increment by loading are similar to undamaged situation. Figure 6 shows a relationship between applied load and average strain. The intension of load increment also shows no characteristic of the yield at an early stage of loading. These facts conclude that there is possibility that yield was not caused by AAR expansion.

Strain of some locations show great value in the early distribution. If there are cracks by AAR a around reinforcing bar, this local behaviour can happen because damage of concrete by crack affects bond mechanism. However, locations of the local behaviour do not agree with locations where greater expansion than near location is observed. The main cause is still unclear because there is also a possibility that surface cracks do not express the situation of cracks around reinforcing bar.

4.2 Average behaviour of concrete

Figure 7 shows the relationship between average concrete stress and average strain. Average concrete stress is calculated with steel stress at a cracked section and average steel stress [3]. In this study, the initial stress and strain caused by AAR expansion is neglected and reinforcing bar is assumed to have no yield to simplify. Actually, the average steel stress-strain relation starts as a reloading after yield in ordered to AAR expansion when a RC member starts to be loaded. However, the reloading slope of yield steel is almost same as its young's modulus [4]. Therefore, this assumption does not stray from fact so much.

Numerical model of undamaged concrete is also shown in the figure for comparison. A line displayed in the figure is a tension stiffening model proposed by Okamura et al [3], which is expressed as follows

$$\sigma_t = f_t \left(\frac{\varepsilon_t}{\varepsilon_{tu}} \right)^c \qquad (1)$$

Where, f_t : tensile strength of concrete, ε_{tu} : cracking strain equal to 0.02 % and c : a constant depending on bond characteristic, 0.4 for deformed bars.

Young's modulus and compressive strength of concrete cylinders subjected to AAR are used in the calculation here. Concrete tensile strength is proposed with the compressive strength [2].

A clear decrease of slope from initial one appears among all specimens unlike undamaged concrete. Secondary decrease of the slope also appears and this decrease is greater than first one. In the tension-stiffening model, stress is constant after reaching the tensile strength. All specimens except T16-020 show similar behaviour like this model. T16-014 and T22-020 also shows a stress drop like the model. However, strain at the starting of stress drop is far greater that strain of the model, 0.02 %.

5 PARAMETRICAL ANALYSIS

5.1 Characteristic factors in concrete tensile behaviour

The relationship between average concrete stress and average strain of test results can be divided into 4 regions and expressed with 8 factors shown in Figure 8. It is difficult to determine ε_2 and σ_2 in T16-020 because no slope close to zero is seen and the region III is unclear. To define the region III clearly, crack opening under the loading is focused. Figure 9 shows the relationship between total longitudinal displacement of concrete surface and average strain in the loading test. Total concrete displacement here also means a summation of crack width. All relationships show a characteristic strain, from which cracks start to open clearly. From comparison with crack opening and average behaviour, it is found that the start of crack opening is very close to the start of region III in specimens where region III is seen clearly. If it is assumed that the start of crack opening agrees start of region III, the greatest decrease of the slope is the start of region III in T19-020. Therefore, average strain of the start of this decrease is decided as ε_2 of T19-020.

Another issue is a determination of ε_t. If the behaviour of concrete crack opening is focused again, clear sudden increase of crack width is also shown in T16-014 and T16-020. This start of sudden increase agrees with the drop of average stress in T16-014. Therefore, it is assumed that the sudden increase of crack width indicates the stress drop in the average behaviour and value of ε_t can be obtained. From these definitions, tension stiffening behaviour does not appear in this test result and the future study is expected to clarify the tension stiffening behaviour.

Finally, all values of factors are obtained from test results. Table 7 shows them.

5.2 Formularization of concrete tensile behaviour

At first, the factors on the region I and II are analyzed. The initial slope of experimental results is lower than Young's modulus of damaged concrete cylinder, whose confinement is free under AAR expansion. Decrease of force transferred to concrete is considered to cause this decrease of the initial slope. It is thought that AAR cracks along a reinforcing bar decrease the confinement effect of concrete around the bar and transferred force will decrease in the result. Therefore, the crack width and the decrease of the slope must be connected. It is assumed that AAR expansion, which is almost recognized as the crack opening, is influenced by reinforcement ratio, bond length and cover depth. Bond length and cover depth is related to bond condition. When bond condition is disrupted, internal stress caused by AAR expansion is not transferred to reinforcing bars enough and confinement effect by reinforcing bar does not appear. Now, a coefficient *a* is defined as the product of the reinforcement (*p*), the cover depth normalized by member length (*C/L*) and bond length (*D/L*).

$$\alpha = p \cdot \left(\frac{D}{L}\right) \cdot \left(\frac{C}{L}\right) \quad (2)$$

Where, *p*: reinforcement ratio (%), *D*: diameter of reinforcing bar (mm), *C*: cover depth (mm), *L*: length of member (mm)

Figure 10 shows the relationship between averaged expansions caused by AAR and the coefficient α. A linear relationship with the longitudinal expansion is shown in the figure and Eq.3 is derived.

$$\varepsilon_{l\,\exp} = -7.65\alpha + 1.114 \times 10^{-3} \quad (3)$$

Where, $\varepsilon_{l\,exp}$: longitudinal strain by AAR expansion

However, no clear relationship is seen about crosswise expansion. Longitudinal confinement degree, which appears as different of longitudinal expansion, is related with crosswise expansion. Therefore, there are other factors connecting crosswise expansion to longitudinal direction. More data are required to clarify this relationship.

Initial and secondary Young's modulus of averaged concrete, E_1 and E_2, is thought to be controlled mainly by bond condition. The relationship between the coefficient and these modulus is investigated in Figure 11 because bond condition is also influenced by damage of AAR expansion and the coefficient relates to longitudinal expansion. In the figure, each modulus is normalized by an undamaged young's modulus, E_1/E_c and E_2/E_c. Strong relationships are observed there. E_1 and E_2 are derived as following equations.

$$E_1 = E_c\left[0.2 + 15.8(\alpha/10^{-6})^{-1.5}\right] \quad (4)$$

$$E_2 = E_c\left[15.8(\alpha/10^{-6})^{-1.5}\right] = E_1 - 0.2E_c \quad (5)$$

Where, E_c is Young's modulus of undamaged concrete cylinder. 2600 kN/mm² is used here. This relationship shows that degrease of the slope in average behaviour of concrete subjected to AAR is controlled by AAR expansion in the axial direction of reinforcing bar.

Eq.4 is expressed as translation of Eq.5 here. If actual phenomenon is considered, E_1/E_c and E_2/E_c don't exceed 1.0 and E_1/E_c doesn't become 0. Above equations meet these conditions.

The strain at changing of initial slope, ε_1 has also an association with initial slope, E_1. The relationship between them is shown in Figure 12. ε_1 is derived as a following liner function of E_1/E_c.

$$\varepsilon_1 = 10^{-6}\left[-330\left(\frac{E_1}{E_c}\right) + 250\right] \quad (6)$$

This equation has an issue that ε_1 becomes 0 before E_1/E_c reaches 1.0. The behaviour in the extent where E_1/E_c exceeds 0.6 and no experimental data exists must be clarified.

Constant stress in region III means tensile strength of concrete subjected to AAR. Tensile strength of concrete subjected to AAR will be varied by crack direction and cannot be expressed easily with cylinder property having random cracks. However, it is difficult to find some relationships with other experiment data in this study. Therefore, formularization of the tensile stress is not discussed in this study.

Strain at drop of average stress is obtained from results of only two specimens. The experiment data is not enough to formularize this strain though there is likely a relationship between this strain and the expansion and formularization of this stain is also not discussed in this study, as the tensile stress.

Finally, the average concrete stress – strain relationship calculated with formulations obtained is shown in Figure 13. In this study, a half of 8 factors expressing average tensile behaviour of concrete in RC member subjected to AAR are formularized with simple method like regression analysis. Moreover, concrete tensile behaviour damaged by AAR can be connected with AAR damage, such as the relationship between slopes before peak stress and AAR longitudinal expansion. However, there still remain issues to formularize significant characteristic factors like peak stress except the factors formularized in this study and to clarify the relationship between longitudinal and crosswise expansion and the characteristics of tension stiffening of AAR damaged concrete.

6 CONCLUSIONS

In this study, one-dimensional tensile behaviour of RC subjected to AAR is investigated with one-dimensional tensile test of reinforced concrete members subjected to Alkali Aggregate Reaction. The following conclusions were obtained from this study.

1) AAR expansion in crosswise to a reinforcing bar is much greater than that parallel to the bar.
2) AAR expansion parallel to the reinforcing bar is formularized with coefficient α involving reinforcement ratio, bond length and cover depth and expressing confinement effect of steel and bond condition.
3) The relationship between average tensile stress and strain of concrete in RC member is different from that of undamaged concrete and the relationship can be divided into 4 regions expressed by 8 factors.
4) Behaviour of crack opening in tensile loading relates to reaching of tensile strength and starting of stress drop in the relationship between average tensile concrete stress and strain in RC member.
5) Initial and secondary slope is also formularized with the coefficient α. Therefore, crack width as a damage of AAR is connected with tensile behaviour of concrete in RC member with the coefficient α quantitatively.

7 REFERENCES

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TABLE 1: Factors considered in the experiment.

Specimen No.	Cross section, mm × mm	Reinforcing bar	
		Diameter, mm	Ratio, %
T16-014	120 × 120	16	1.40
T16-020	100 × 100		2.00
T19-020	120 × 120	19	
T22-020	140 × 140	22	

TABLE 2: Property of reinforcing bars.

Diameter, mm	Young's modulus kN/mm²	Yield	
		Stress, N/mm²	strain, %
16	195	438	0.22
19	188	403	0.21
22	192	421	0.22

TABLE 3: Property of materials used in concrete.

Material	Kind	Density, g/cm²	Fineness modulus
Cement	Normal Portland	3.16	-
Fine aggregate	River sand	2.59	2.68
Coarse aggregate	Crashed stone	2.73	6.46

TABLE 4: Mixture proportion.

W/C	Unit volume, kg/m³				
	W	C	S	G	NaOH
0.50	180	360	813	930	6

TABLE 5: Concrete properties in the AAR acceleration procedure.

Submerged-days	0	20	45
Compressive strength, N/mm²	25.2	33.3	30.0
Young's modulus, kN/mm²	26.4	21.4	16.8
Poisson's ratio	-	0.20	0.25
*: The procedure was terminated at 45th day.			

TABLE 6: Concrete average strain caused by AAR expansion.

	T16-014	T16-020	T19-020	T22-020	Cylinder
Longitudinal, μ	435	200	920	308	1433
Crosswise, μ	1144	-	5509	3933	-

TABLE 7: Factors in tensile behavior.

	T16-014	T16-020	T19-020	T22-020
E_1, kN/mm^2	15100	12200	8100	7600
E_2, kN/mm^2	7100	7400	5600	2200
E_1/E_c*	0.57	0.46	0.31	0.29
E_2/E_c*	0.27	0.28	0.21	0.08
ε_1, μ	38	130	157	129
σ_1, N/mm^2	0.57	1.56	1.27	0.98
ε_2, μ	281	209	284	470
σ_2, N/mm^2	2.2	2.16	2.03	1.82
ε_t, μ	488	581	-	-

* E_c: Young's modulus of undamaged concrete cylinder

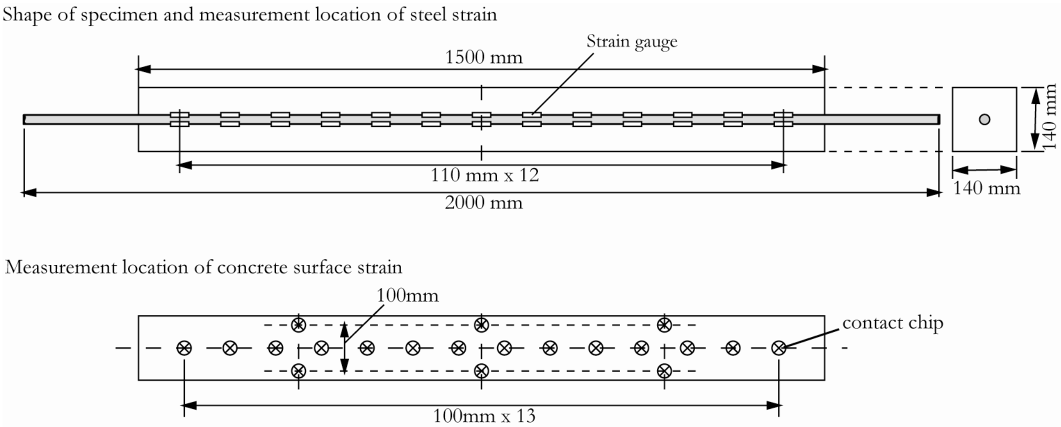

Figure 1: Shape of one of test specimens (T22-020).

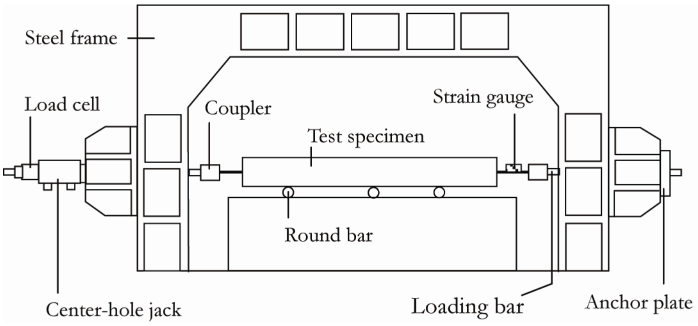

Figure 2: Test setup.

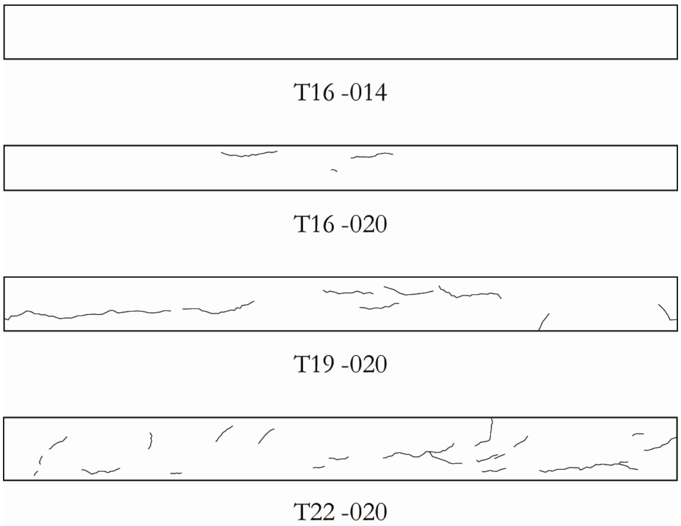

Figure 3: Crack pattern.

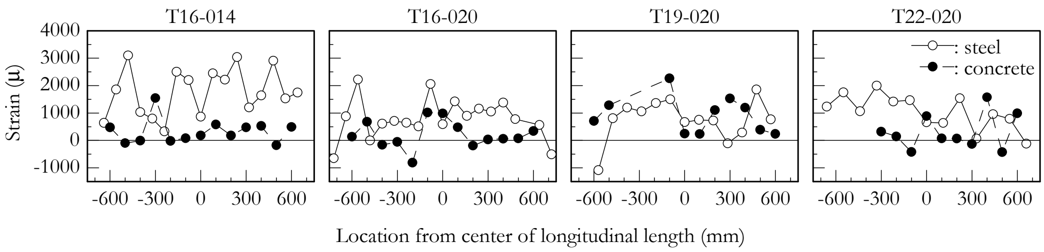

Figure 4: AAR strain distribution of reinforcing bar and concrete surface in the longitudinal direction.

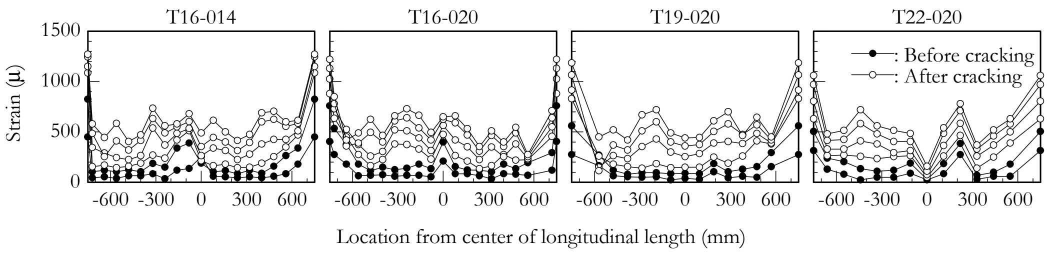

Figure 5: Strain distribution on reinforcing bar under tensile loading.

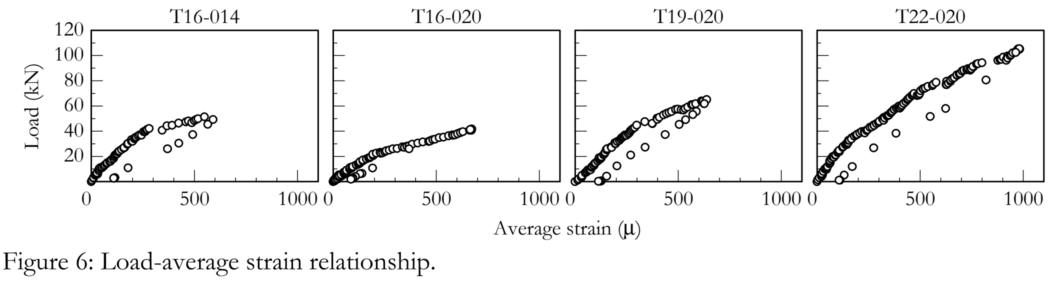

Figure 6: Load-average strain relationship.

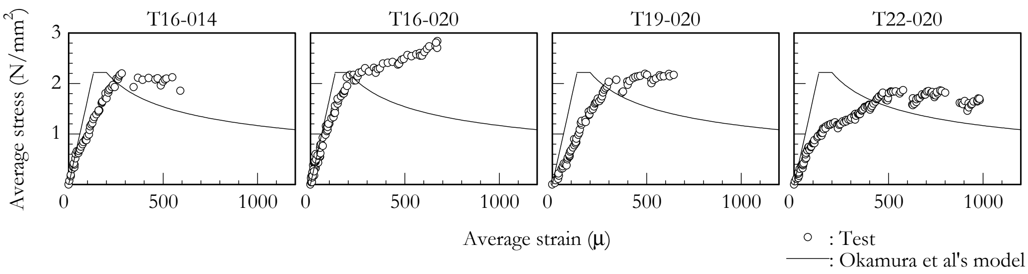

Figure 7: Average concrete stress - average strain relationship.

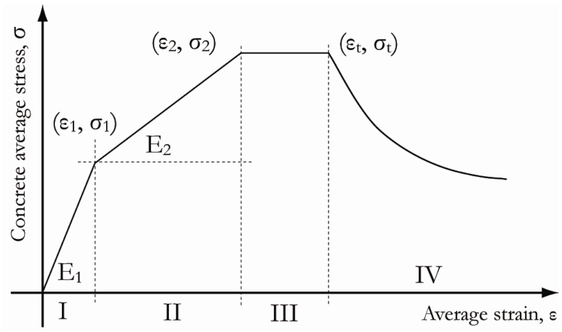

Figure 8: Average stress - strain model of concrete subjected to AAR.

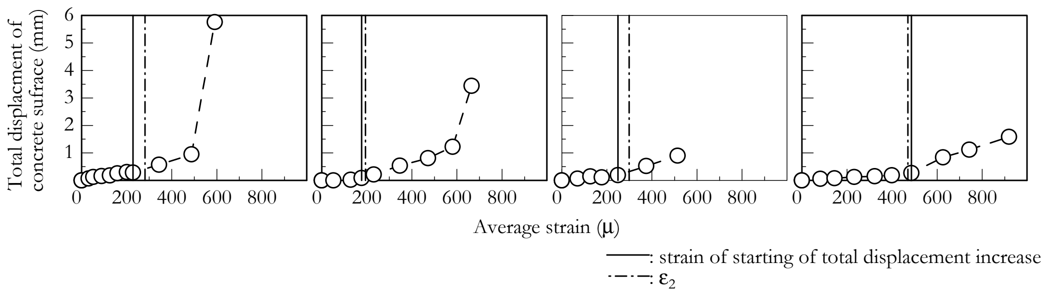

Figure 9: Total displacement of concrete surface - average strain relationship.

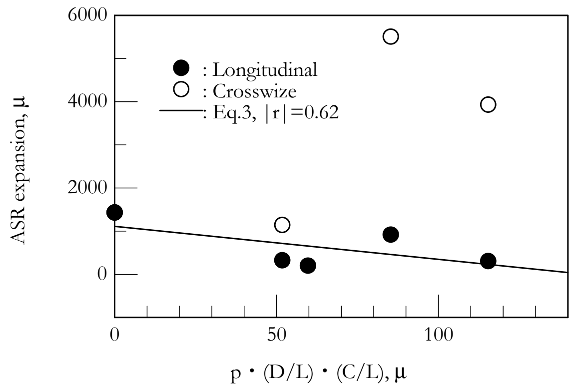

Figure 10: Relationship between coefficient α and AAR expansion.

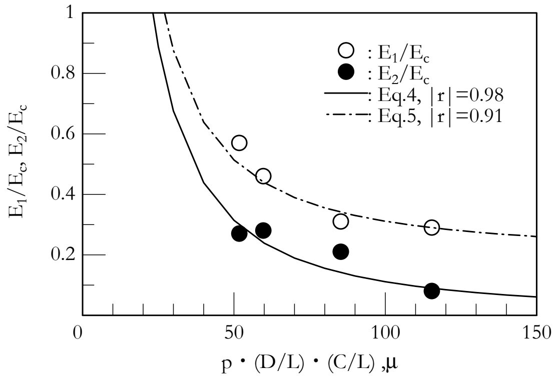

Figure 11: Relationship between Young's modulus of damaged concrete and the coefficient α.

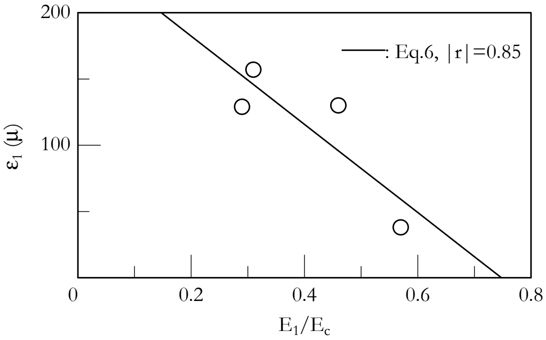

Figure 12: Relationship between E_1 and ε_1.

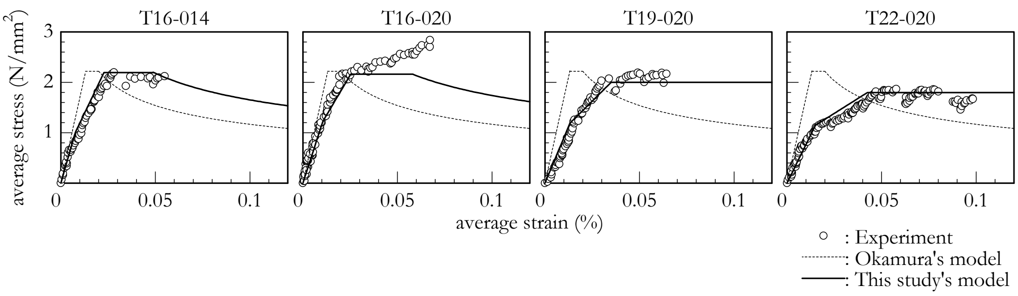

Figure 13: Calculated average concrete stress and strain relationship with factors obtained from parametric analysis.